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LIFT LOSSES FOR FIN-BODY GAPS IN TRANSONIC AND SUPERSONIC SPEEDS: DATA CORRELATION AND MODELING

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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

An algebraic model is established to predict the fin lift losses due to fin-body gaps for missiles and projectiles in transonic and supersonic speeds. The model is based on two distinct correlations which were established using wind tunnel results. The first correlation is for transonic speeds ($0.8 < M < 1.2$) and for large fin gap heights ($g/D > 0.08$). This extends the earlier work of Mikhail which was only valid for gap heights, $g/D < 0.08$. The second correlation is for both small and large gaps at supersonic speeds ($1.2 < M < 4$). Both correlations use the physical parameters of the fin as well as the flow conditions. The results obtained using these two correlations are very satisfactory when compared with the data that they represent. There is no alternate approach in the literature that can predict these results. The correlations cover all shapes of fin planforms with moderate aspect ratios (0.5 to 4.0) and all heights of streamwise gaps. A factor which represents the effects of the

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19. ABSTRACT (Continued)

fin in producing lift (normal force for the body-fin combination) in the presence of a fin-body gap is computed. This factor provides a direct estimate of the fin lift losses which, in turn, is to be used in determining the static stability of the missile or finned projectile. The present model includes viscosity and fin support interference effects based on actual wind tunnel measurements which, of course, encompass both effects. The present analysis utilizes very simple algebraic models which can be easily implemented in any fast aerodynamic prediction code for missiles and projectiles. Eighteen cases were validated against experiments using the present two models. The accuracy of the model is ± 7.0% based on all the cases considered.

TABLE OF CONTENTS

LIST OF FIGURES

I. INTRODUCTION

There has been an increasing interest by the Army in "smart munitions". Smart munitions are those guided to their targets by laser, millimeter wave, radar or some other means. They require in-flight controllability which is usually achieved by rotatable control surfaces (fins/tails/wings/canards). These surfaces usually require some small gaps or "clearances" with the body of the projectile as depicted in Figure 1. These "small" gaps always result in loss of lift produced by the fins, thus reducing fin effectiveness. These losses were studied in detail by Mikhail[1] for the transonic speed regime (M = 0.8-1.2) and small gaps ($g/D < 0.08$ where D is the body diameter). The specific range of interest of Reference 1 was dictated by the Copperhead guided-projectile case study. The correlation of Reference 1 is not applicable in the supersonic speed regime (M = 1.2-4.0) or for large gaps ($g/D > 0.08$).

Large gap heights, defined in this study as those with $g > 0.08$ D, are used for reasons other than body clearance. For maneuverability of guided missiles and projectiles, the vehicle must be less statically stable so that the required control surface can be small and yet sufficient to "steer" the vehicle into its desired path. To reduce static stability in the guided phase of the vehicle, a fin-body gap may be created by actuators that push the fins away from the body. These gaps are usually larger than those required only to clear the body to allow the motion of the fin.

The present study covers the Mach number and gap height ranges which were not covered in Reference 1. Figure 2 shows the small range of applicability of Reference 1, as given by Region I, while the present study covers Regions II and III.

The present work utilizes the data of Reference 2 which provides data for missiles with and without gaps for the present ranges of study. References 3-5 provide additional experimental data. However, unlike their use in Reference 1, they cannot be used in this study. Their Mach range and gap heights were covered and used for the range of interest of Reference 1.

Some earlier analytic work was done, primarily for supersonic speeds. This work usually neglects viscosity effects, which are very dominant for the small gaps, and also neglect the fin-body support effects. The present analysis avoids these two difficult-to-predict phenomena by utilizing measured data where these effects are both included. Bleviss and Struble[6] in 1953 presented an inviscid analysis of gap losses for triangular fins in supersonic speeds. The analysis is only valid for triangular fins and neglects viscosity and fin support interference effects. It also assumes a long afterbody extending beyond the fin location. Mirles,[7] almost at the same time, presented a slender body analytic solution for the fin lift losses with the same limitations of: a triangular fin; long afterbody behind the fins; no viscosity; and no fin support interference. Dugan and Hikido,[8] shortly after in 1954, presented a slender body analysis for gap effects for triangular fins mounted on long afterbodies with no viscosity or fin support interference effects considered. A more recent analytic work was done by August[9] in 1982, who used the inviscid supersonic analysis of Bleviss and Struble and the questionable results of Hoerner,[10] to estimate the normal force losses for streamwise gaps. The application was made to the typical triangular fin of aspect ratio 1.0. August applied the analysis to the Sidewinder missile geometry at M = 2.5 for

the triangular canard fin with fin deflection. The gap area was estimated and equalized by a streamwise gap area. This application was done during the development of a fast aerodynamic design code. Sun, et al,[11] in 1984, re-iterated the results of August and made an application to a missile configuration at $M = 1.2$ and 2.0 using the same computer code. In both cases of References 9 and 11, no details of the geometry and test conditions were given; nor was a systematic calculation procedure stating the limitations and restrictions disclosed.

It is the purpose of this work to systematically account for the lift (or normal force at zero angle of attack) loss due to streamwise fin-body gaps for large and small gaps in both the transonic and supersonic speed regimes. This work complements the earlier work of Reference 1 and completes the coverage of the fin loss for all speed regimes and most gap heights of practical interest.

II. ANALYSIS

Two distinct areas of analysis are performed. The first is for large gaps ($g/D \geq 0.08$) in transonic speeds ($0.8 \leq M \leq 1.2$). The second is for supersonic speeds ($1.2 < M < 4$) and for any size gap (both small and large). For a body-tail combination one can model the effects of gaps by writing[1]:

$$C_{N_{BT}} = C_{N_B} + FNF \cdot (K_{T(B)} + (K_{B(T)}) \cdot C_{N_T} \tag{1}$$

where the FNF is the Fin Normal Force correction factor ($0 < FNF \leq 1.0$) and defined (for small α) as:

$$FNF = \frac{C_{N_{fg}}}{C_{N_f}} = \frac{C_{N_{\alpha fg}}}{C_{N_{\alpha f}}} \tag{2}$$

where $C_{N_{fg}}$ is the normal force coefficient of the fin in the presence of a gap height "g".

The gap effect for an unknown case, FNF_2, was correlated to the value of a known case, FNF_1, by the relation:

$$FNF_2 = CF \cdot FNF_1 \tag{3}$$

where CF is the Correlation Factor written as:

$$CF = (SF \cdot AF \cdot GF \cdot CSF \cdot BF) \tag{4}$$

where SF, AF, GF, CSF and BF are the shape, fin area, gap, chord/span, and boundary layer factors, respectively.

The subscripts 1 and 2 will be used throughout this work to denote the known and unknown cases, respectively.

1. LARGE GAPS (g/D > 0.08) IN TRANSONIC SPEEDS (M = 0.8-1.2)

This analysis modifies the expressions of Reference 1 which is only valid for small gaps (g/D < 0.08). For large gaps, it was found that only modifications to the shape, gap and chord/span factors were required. The new forms for these factors are:

$$SF = \left\{ \frac{\left[\left(\dfrac{0.76A_{20} + A_{22}}{A_{22}}\right) + \dfrac{0.24A_{20}(A_{22} - A_{11})}{(0.5b_2c_2)(0.5b_2c_2 - 0.5b_1c_1)}\right]}{\left[\left(\dfrac{0.76A_{10} + A_{11}}{A_{11}}\right) + \dfrac{0.24A_{10}(A_{22} - A_{11})}{(0.5b_1c_1)(0.5b_2c_2 - 0.5b_1c_1)}\right]} \right\}^{0.85} \tag{5a}$$

$$GF = \left(\frac{(g/D)_1}{(g/D)_2}\right)^{.2} \tag{5b}$$

$$CSF = \sqrt{\left(\frac{b_2}{b_1}\right)\left(\frac{c_2}{c_1}\right)^{1.5}} \tag{5c}$$

The remaining two factors, AF and BF are unchanged and are given by the expressions:

$$AF = \frac{A_1}{A_2} \tag{5d}$$

and

$$BF = \left(\frac{\delta_{LE2}}{\delta_{LE1}}\right)^{.88} \tag{5e}$$

where the boundary layer thickness, δ_{LE}, was estimated by the familiar form[12] for turbulent boundary layers in axisymmetric tubes:

$$\delta_{LE1} = 0.37 \frac{X_{LE1}}{\left(R_{e_{XLE1}}\right)^{.2}}$$

The reference case for FNF_1 is the triangular fin of aspect ratio 1.5 of Reference 2 with $(g/D)_1 = 0.06$, $b_1 = 0.525$ inch, $c_1 = 1.4$ inch, $A_{11} = 0.3675$ $(inch)^2$, $A_{20} = 0.3675$ $(inch)^2$, and $FNF_1 = 0.795$.

One would notice that the three new expressions (5a, 5b, 5c) represent simple modifications to the original expressions of the small gaps. The power of 0.85 was used instead of 1.0 for the shape factor, SF. The GF factor power was simplified to 0.2 instead of the earlier form:

$$\frac{1}{\left[1.6 - \left(\frac{(g/D)_1}{(g/D)_2}\right) \cdot \left(\frac{(g/D)_2 - 0.04}{0.05}\right)\right]} \quad .$$

Finally, the power 1.5 was used in the CSF factor, Equation (5c), instead of 1.0.

The new GF function for large gaps differs significantly in value compared to the corresponding GF function of Reference 1 for small gaps. The two functions are plotted in Figure 3. This large gap model must be used for $g/D >$ 0.08, while the small gap model must be used for $g/D < 0.06$. For $0.06 < g/D <$ 0.08 either function may be used, but only together with its associate formulae.

One should notice the absence of Mach number dependency, a fact which was established in Reference 1 for the transonic speed regime ($M = 0.8-1.2$). This observation will not be true for the supersonic speed regime, as will be shown next.

2. LARGE AND SMALL GAPS IN SUPERSONIC SPEEDS (M = 1.2-4.0)

It was found, by examining the data of Reference 2, that the Mach number independence of FNF can be extended to $M = 1.8$ as indicated in Figure 4. The data also showed linear behavior in the Mach range 1.8 to 4.0. Therefore, if the value of FNF is predicted at $M = 4.0$ (point D), then the FNF can be easily computed over the supersonic region between $M = 1.2$ and 4.0.

The data available at Mach 4.0 in Reference 2 were less in number than those available from the same reference for $M = 3.0$ (point C). Therefore, the correlation was based on the data at $M = 3.0$. The model then linearly extends the value to $M = 5.0$ as shown in Figure 4. The value of FNF at $M = 1.8$ (point B) is already known for small gaps (Reference 1) and for large gaps (from the above section).

The FNF model at Mach 3.0 was constructed in a similar manner as that of Reference 1, however, with some parameters being changed. First, the shape factor was not influential and the Reynolds number dependency was very weak. The wind tunnel data correlated better using the aspect ratio parameter, AR, rather than the previously used area factor. Also, the chord/span parameter showed a direct dependency only on the fin root chord c. The fin span parameter was absorbed (implicitly) in the aspect ratio parameter.

Finally, the FNF_2 at Mach 3.0 was obtained as:

$$\left. FNF_2 \right|_{M=3} = CF \cdot \left. FNF_1 \right|_{M=3}$$

$$= \left[\left(\frac{(g/D)_1}{(g/D)_2} \right)^{.15} \left(\frac{AR_2}{AR_1} \right)^{.2} \left(\frac{c_1}{c_2} \right)^{.4} \right] \cdot \left. FNF_1 \right|_{M=3} \quad . \tag{6}$$

The reference case values are the values for the case of the triangular fin of Reference 2 at M = 3 with the following parameters:

$$(g/D)_1 = 0.06, \; AR_1 = 1.5, \; c_1 = 1.4 \text{ inch},$$

$$b_1 = 0.525 \text{ inch, and } \left. FNF_1 \right|_{M=3} = 0.851 \; . \tag{7}$$

With the given geometric parameters of the given fin (2) [$(g/D)_2$; AR_2; and c_2], one can directly calculate $\left. FNF_2 \right|_{M=3}$. Then, for any value of Mach number, the linear model of Figure 4 is used to determine the corresponding FNF_2 value. Equation (1) can then be used to calculate the effective normal force for the body-tail combination with the specified gap height.

III. RESULTS

The results provided here are for the configurations and test conditions of Reference 2. The fin geometries and the wind tunnel conditions were provided in detail in Reference 1.

1. LARGE GAPS, TRANSONIC SPEEDS (M = 0.8-1.2)

All cases of Reference 2 were studied. Six cases with large gap heights of 0.12D, 0.16D, 0.20D and 0.25D, for fins with aspect ratios of 0.5, 0.75, 1.0 and 1.5 were computed.

Figure 5 shows the results for the FNF loss factor for the triangular fin of AR = 1.5 and a large gap height of 0.12D. The result of the expression of Equation (5) fits the data very well. The fin effectiveness factor computed (FNF) was 0.69, thus indicating a 31% loss in lift due to the gap.

Figure 6 shows the results for the same fin; but at the larger gap height of 0.20D. The agreement is excellent between the data and the fit provided by the given correlation. A 38% lift loss is observed.

Figures 7 and 8 show the results for a rectangular fin with an aspect ratio of 1.0 and gap heights of 0.16D and 0.25D. The fin effectiveness is 0.70 and 0.64, indicating corresponding lift losses of 30% and 36%, respectively. The results agree with the data very well.

Figures 9 and 10 show the results for a rectangular fin of AR = 0.5 at gap heights of 0.12D and 0.20D. Even at this very small aspect ratio, the results of the established expressions are in excellent agreement with the experimental data. The fin lift effectiveness is 0.76 and 0.69, indicating corresponding lift losses of 24% and 31%, respectively.

2. LARGE AND SMALL GAPS, SUPERSONIC SPEEDS (M = 1.2-4.0)

All test cases of Reference 2 were analyzed. Overall twelve cases were utilized, four of them are for small gaps and eight are for large gaps.

Figure 11 shows the results for a triangular fin of AR = 1.5 with a small gap height of 0.06D. The linear model gave very good agreement with the data. Also the extrapolation at M = 4 proved to be very acceptable. The results indicate a 20% lift loss for transonic speeds, a loss of 15% at M = 3.0, and a loss of 11% at M = 4.0 .

Figures 12 and 13 show the results for the same fin with large gap height settings of 0.12D and 0.20D, respectively. The results of the correlation expression fits the data with very good agreement.

Figures 14, 15 and 16 are for a rectangular fin of AR = 1.0, at gap height settings of 0.08D, 0.16D and 0.25D. The results compare well with the wind tunnel data. Notice the increase in the lift losses in the transonic speeds from 22% to 30% to 37% with the increase in gap height.

Figures 17, 18 and 19 are for a rectangular fin of AR = 0.75 and at gap height settings of 0.06D, 0.12D and 0.20D. The results are generally satisfactory. Note that the lift losses are 50% for the large gap of 0.20D, in the transonic speed regime. This loss was only 30% and 43% when the gaps were 0.06D and 0.12D, respectively.

In general, the results appear very acceptable. For the cases considered, lift losses are predicted within seven percent or less. All the results for the eighteen cases are tabulated in Table 1, together with the wind tunnel data.

TABLE 1. Results of the Present Correlations and Comparison with Wind Tunnel Data.

Case No.	Case Conditions	FNF Wind Tunnel Data (Ref. 2)	FNF Present Correlations	Percent Difference
	I. Transonic Speeds, Large Gaps:			
1	AR = 1.5 g/D = 0.12	0.709	0.692	-2.4%
2	AR = 1.5 g/D = 0.20	0.627	0.625	-0.4%
3	AR = 1.0 g/D = 0.16	0.688	0.703	+2.2%
4	AR = 1.0 g/D = 0.25	0.634	0.643	+1.4%
5	AR = 0.5 g/D = 0.12	0.766	0.764	-0.3%
6	AR = 0.5 g/D = 0.20	0.677	0.689	+1.8%
	II. Supersonic Speed (M = 3), Large and Small Gaps:			
7	AR = 1.5 g/D = 0.06	0.851	0.851	0.0%
8	AR = 1.5 g/D = 0.12	0.775	0.767	-1.0%
9	AR = 1.5 g/D = 0.20	0.685	0.710	+3.6%
10	AR = 1.0 g/D = 0.08	0.850	0.880	+3.6%
11	AR = 1.0 g/D = 0.16	0.816	0.791	-3.8%
12	AR = 1.0 g/D = 0.25	0.767	0.742	-3.1%
13	AR = 0.75 g/D = 0.06	0.734	0.740	+0.8%
14	AR = 0.75 g/D = 0.12	0.691	0.677	-2.0%
15	AR = 0.75 g/D = 0.20	0.659	0.619	-6.1%
16	AR = 0.50 g/D = 0.06	0.724	0.682	-5.8%
17	AR = 0.50 g/D = 0.12	0.620	0.613	-1.1%
18	AR = 0.50 g/D = 0.20	0.534	0.571	+6.9%

IV. SUMMARY AND CONCLUSIONS

An algebraic model was established, based on wind tunnel data correlations, that predicts the normal force losses for fins with large fin-body gaps in transonic and supersonic speeds. The present study covers a much larger range of Mach number and gap heights than those available in the present literature. The results obtained provide very good agreement with the wind tunnel data. This work is for supersonic speeds and provides the missile/projectile designer with a fast prediction method to calculate fin effectiveness in the presence of streamwise gaps.

The analysis covers the Mach range $0.8 < M < 4.0$ and extends the applicability to both small and large fin gap heights. The model can be used up to $M = 5.0$ with care. It has not been validated below $M = 0.7$ and should not be used in that region. The models were validated using eighteen cases from wind tunnel tests. The model is established in simple algebraic formulae that can be easily programmed into any fast aerodynamic prediction code for missiles and projectiles. It is a very satisfying achievement to be able to model a highly complex problem with such simple models.

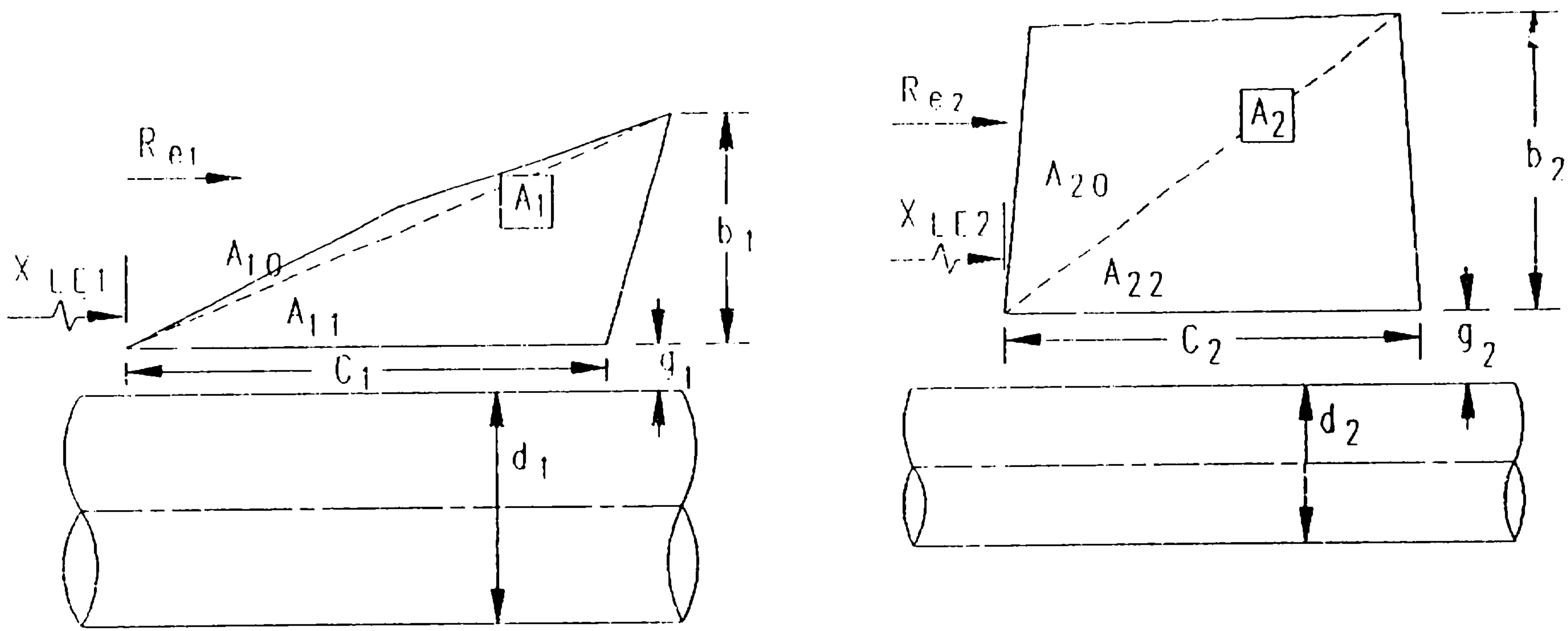

Figure 1. Nomenclature for the fin gap correlation

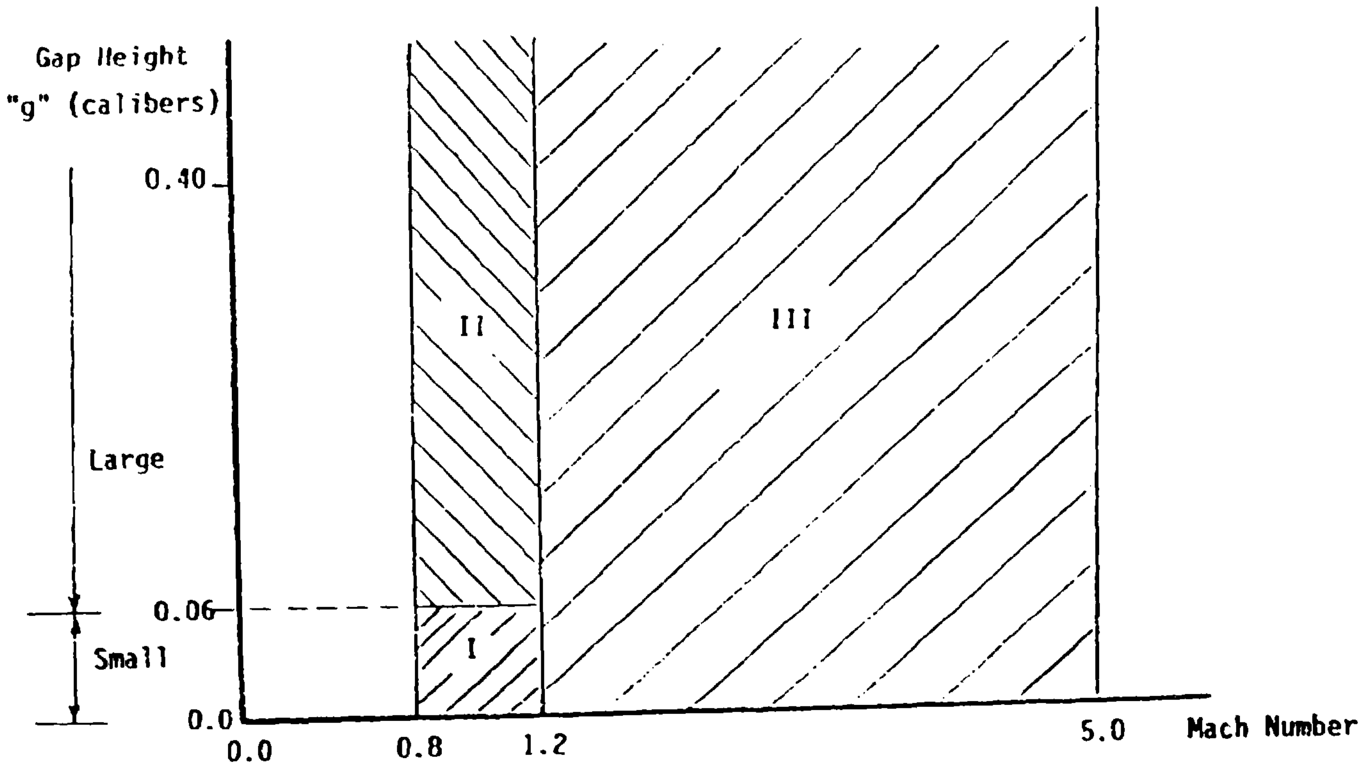

Figure 2. Present range of application (Region II and III) in comparison with the Range of Reference 1 (Range I)

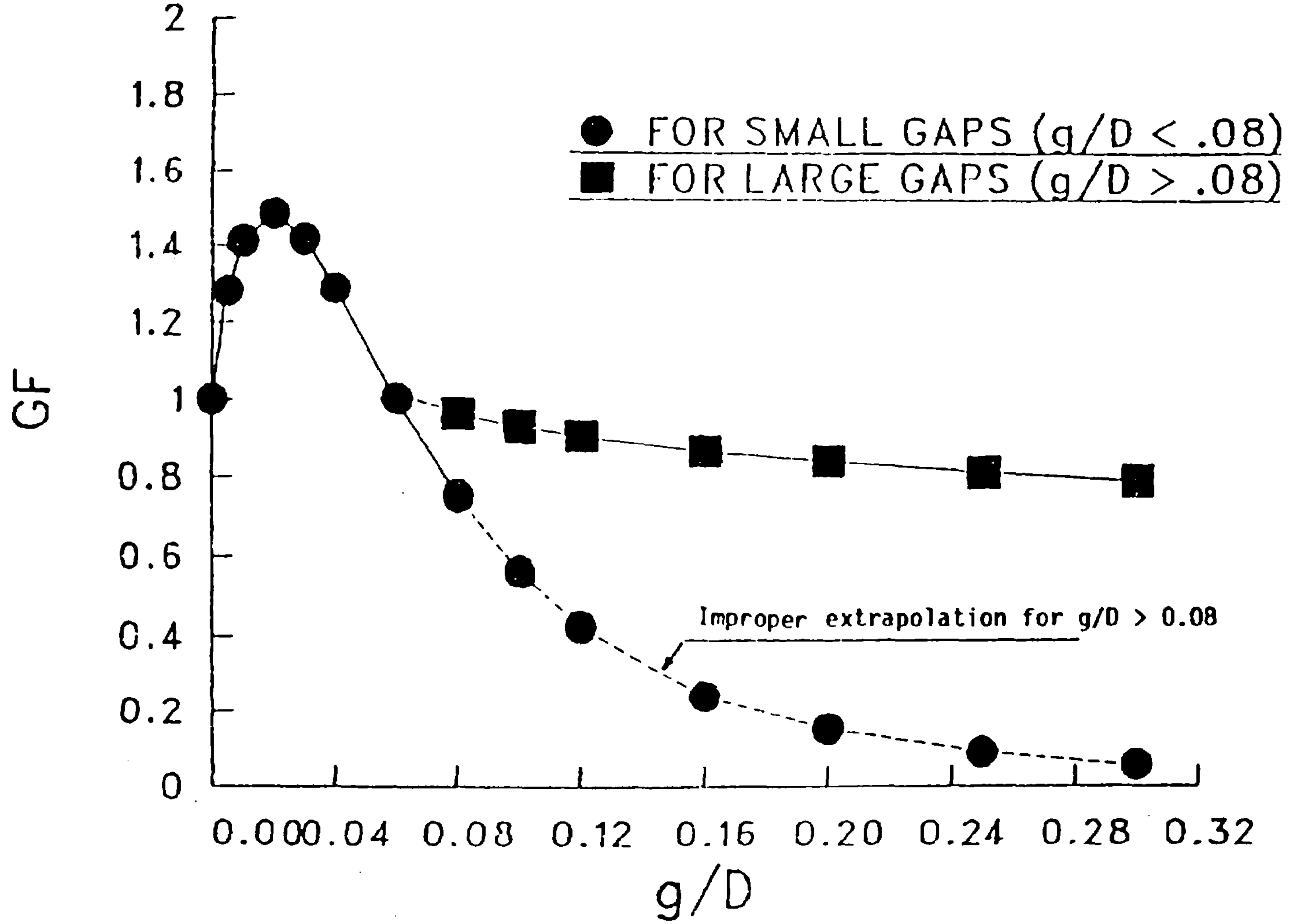

Figure 3. The gap height factor, GF, for transonic speeds and large gaps

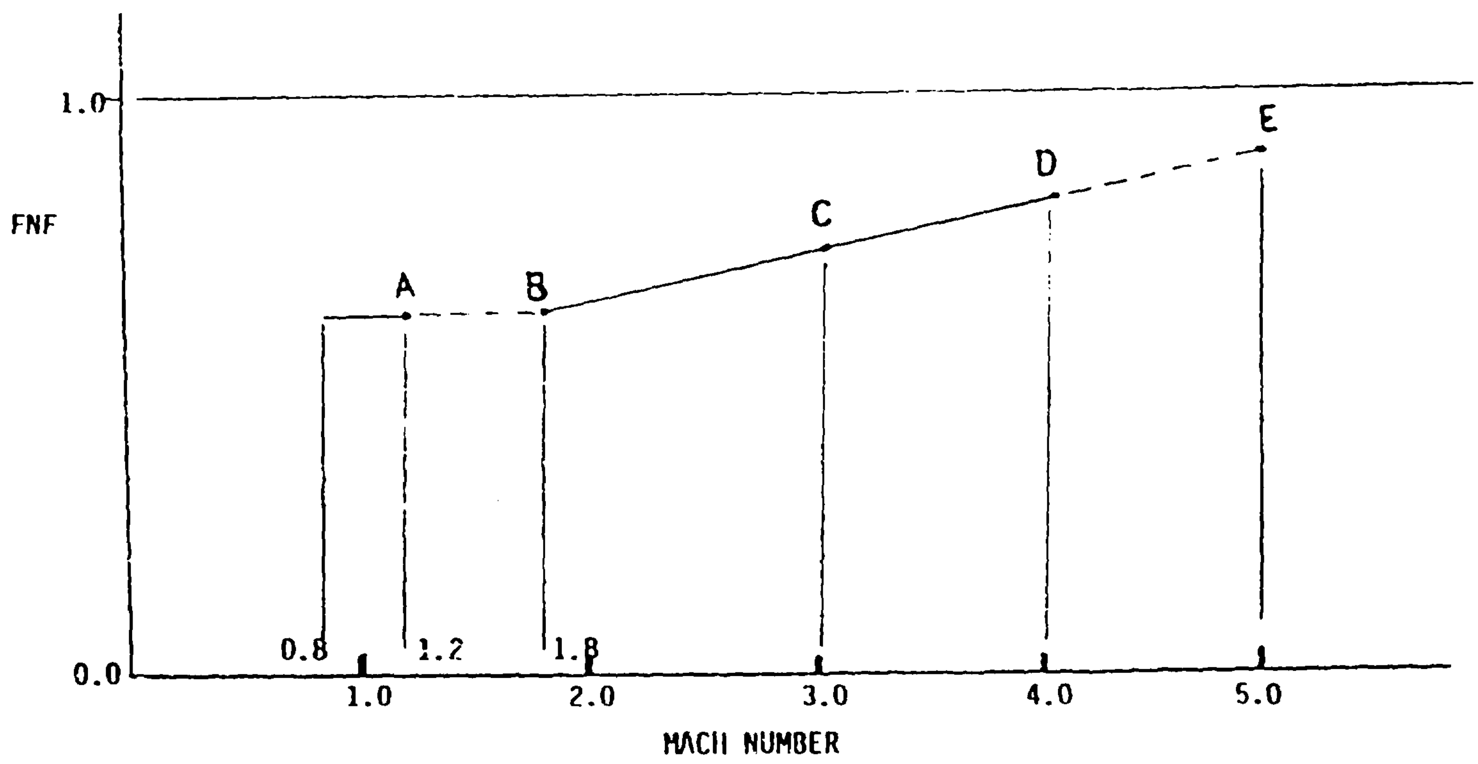

Figure 4. The model for fin normal force losses in supersonic speeds

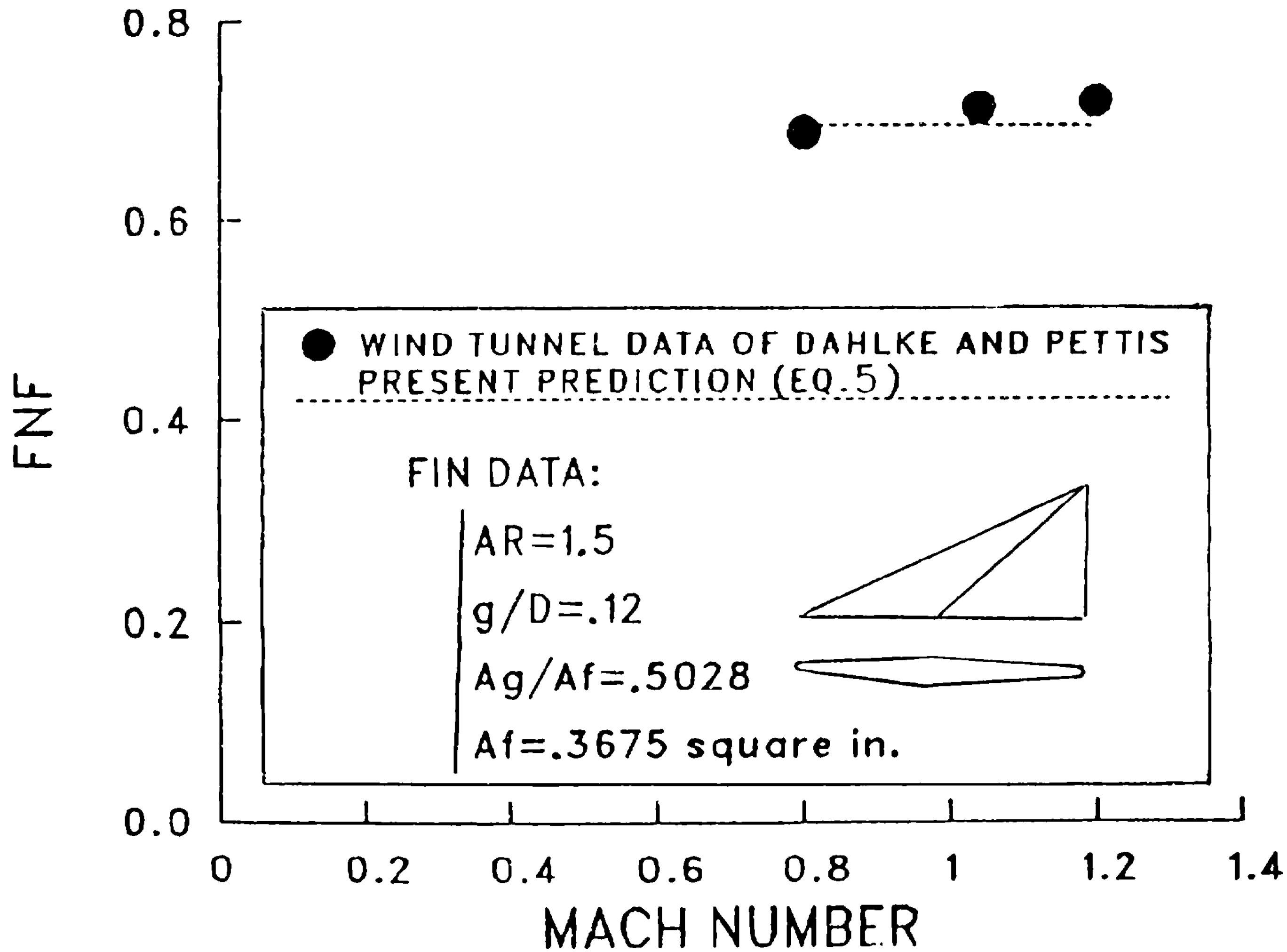

Figure 5. Comparison with data, transonic speeds (AR = 1.5, g/D = 0.12)

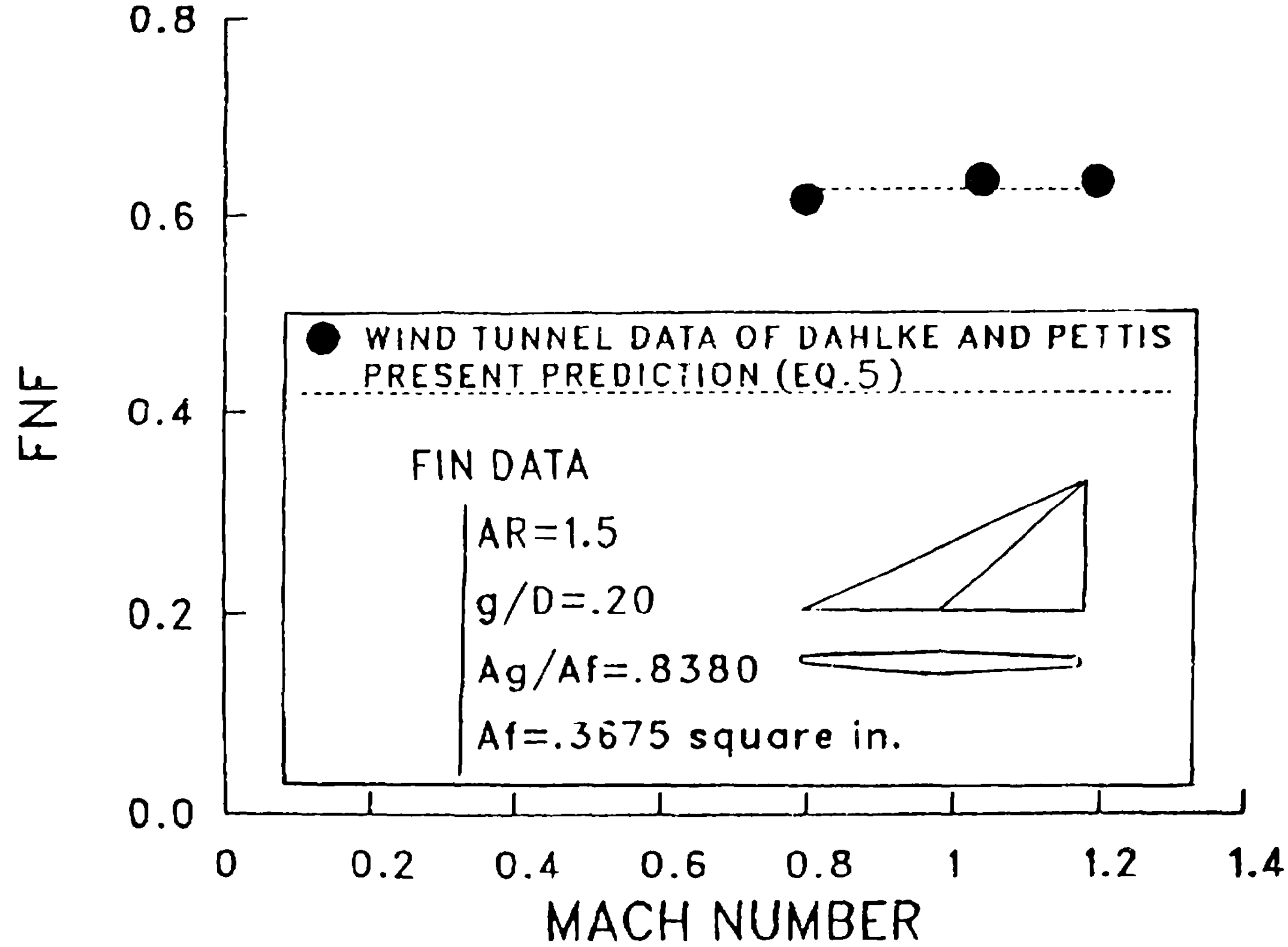

Figure 6. Comparison with data, transonic speeds (AR = 1.5, g/D = 0.20)

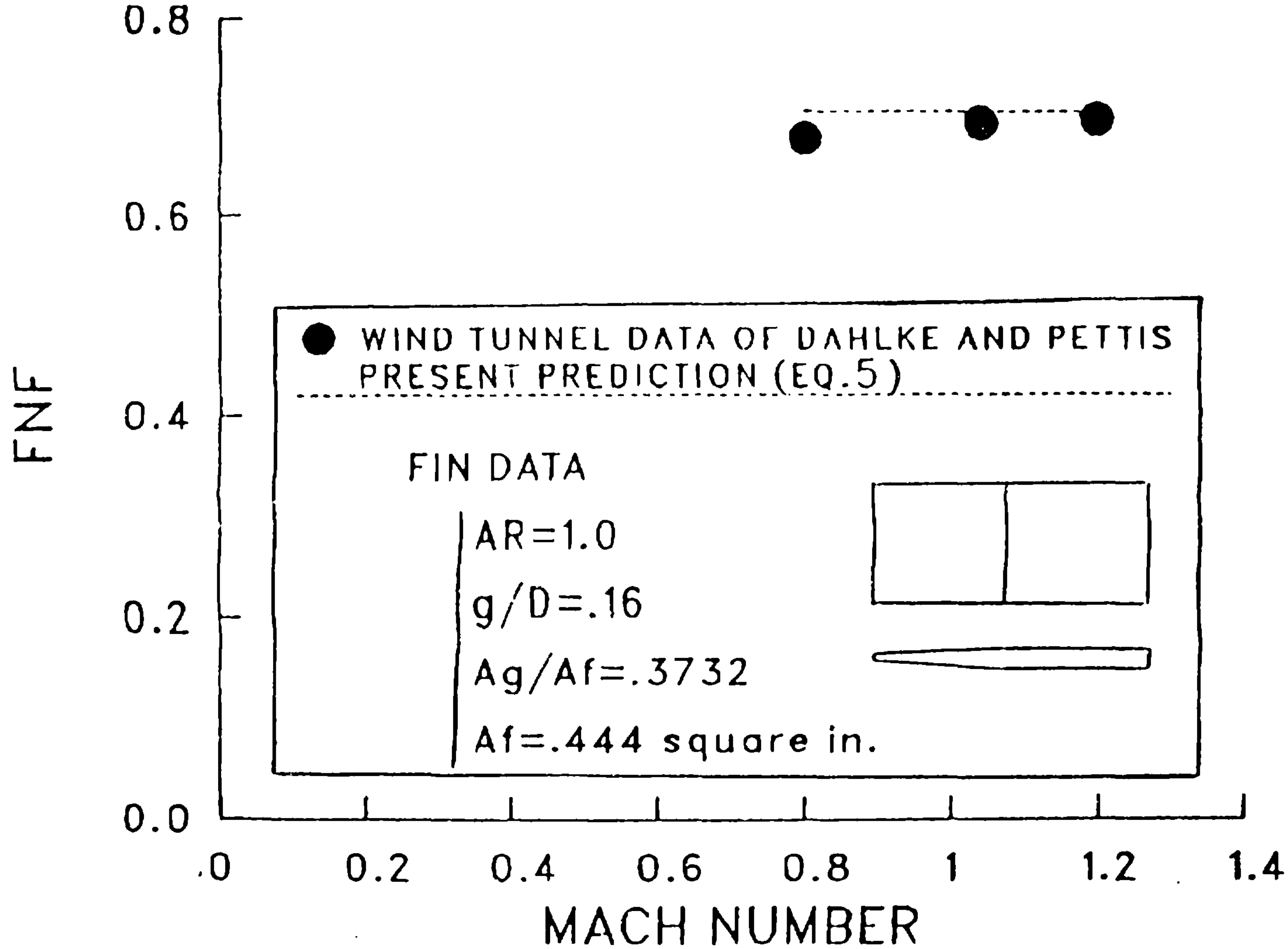

Figure 7. Comparison with data, transonic speeds (AR = 1.0, g/D = 0.16)

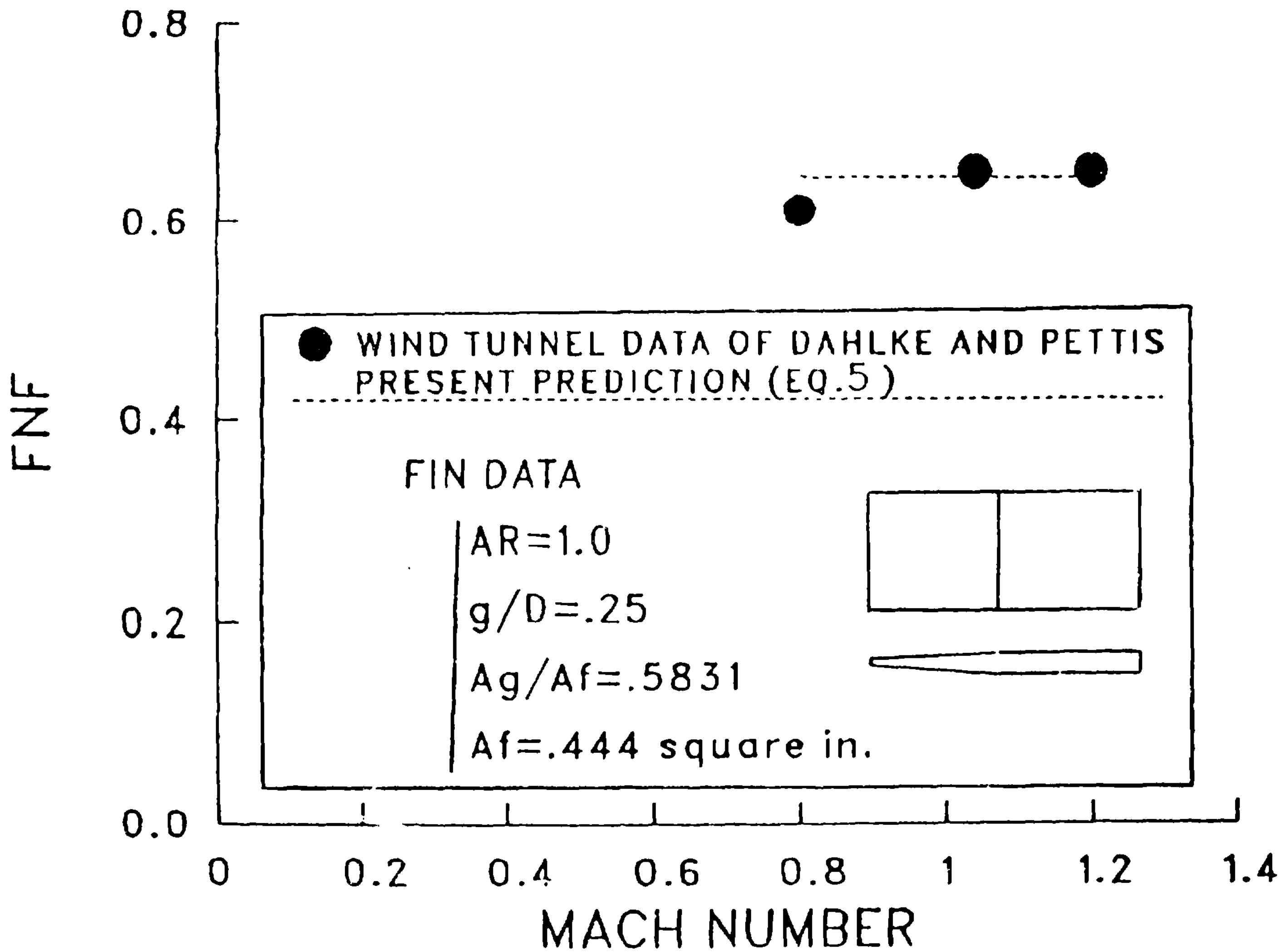

Figure 8. Comparison with data, transonic speeds (AR = 1.0, g/D = 0.25)

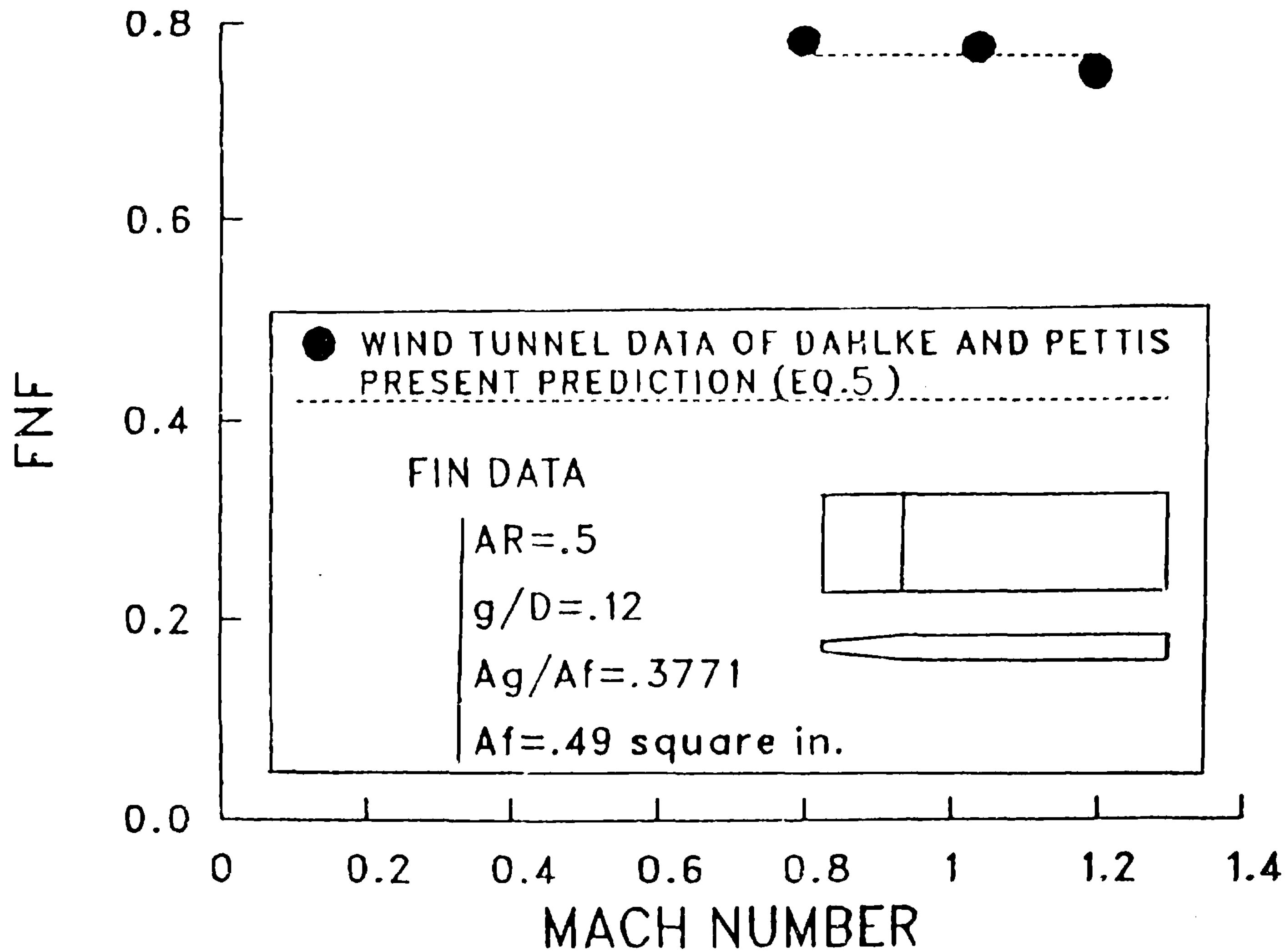

Figure 9. Comparison with data, transonic speeds (AR = 0.5, g/D = 0.12)

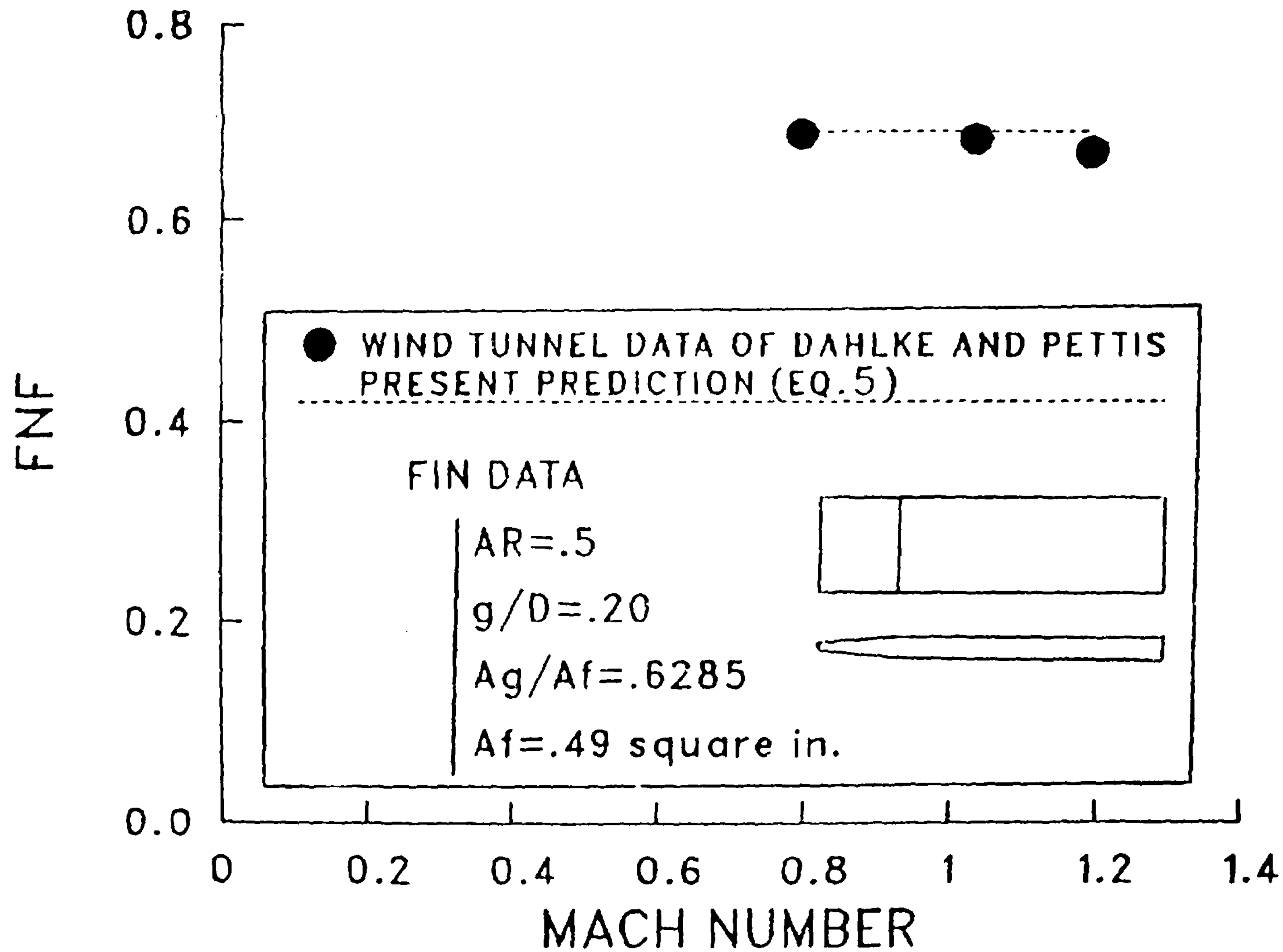

Figure 10. Comparison with data, transonic speeds (AR = 0.5, g/D = 0.20)

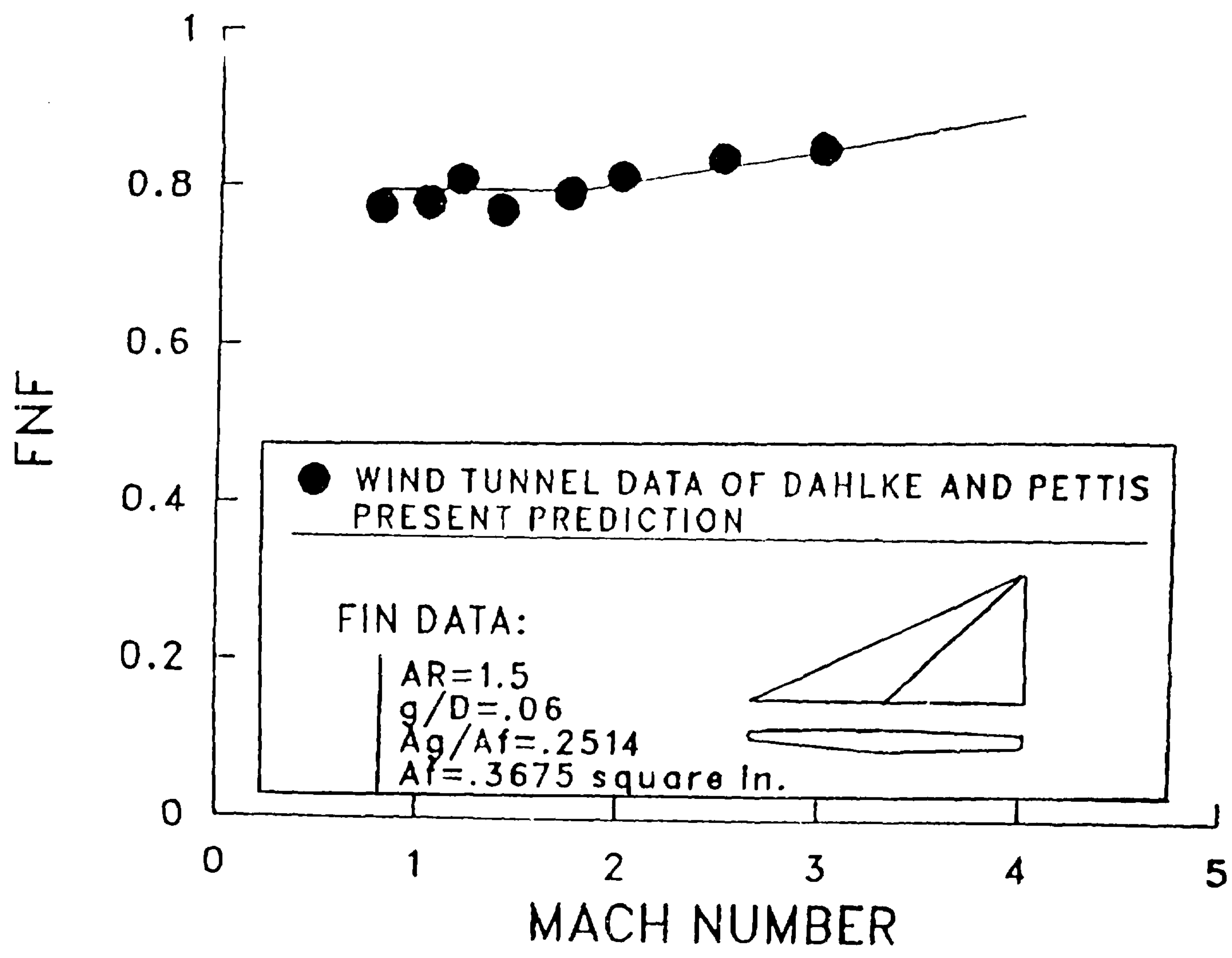

Figure 11. Comparison with data, supersonic speeds (AR = 1.5, g/D = 0.06)

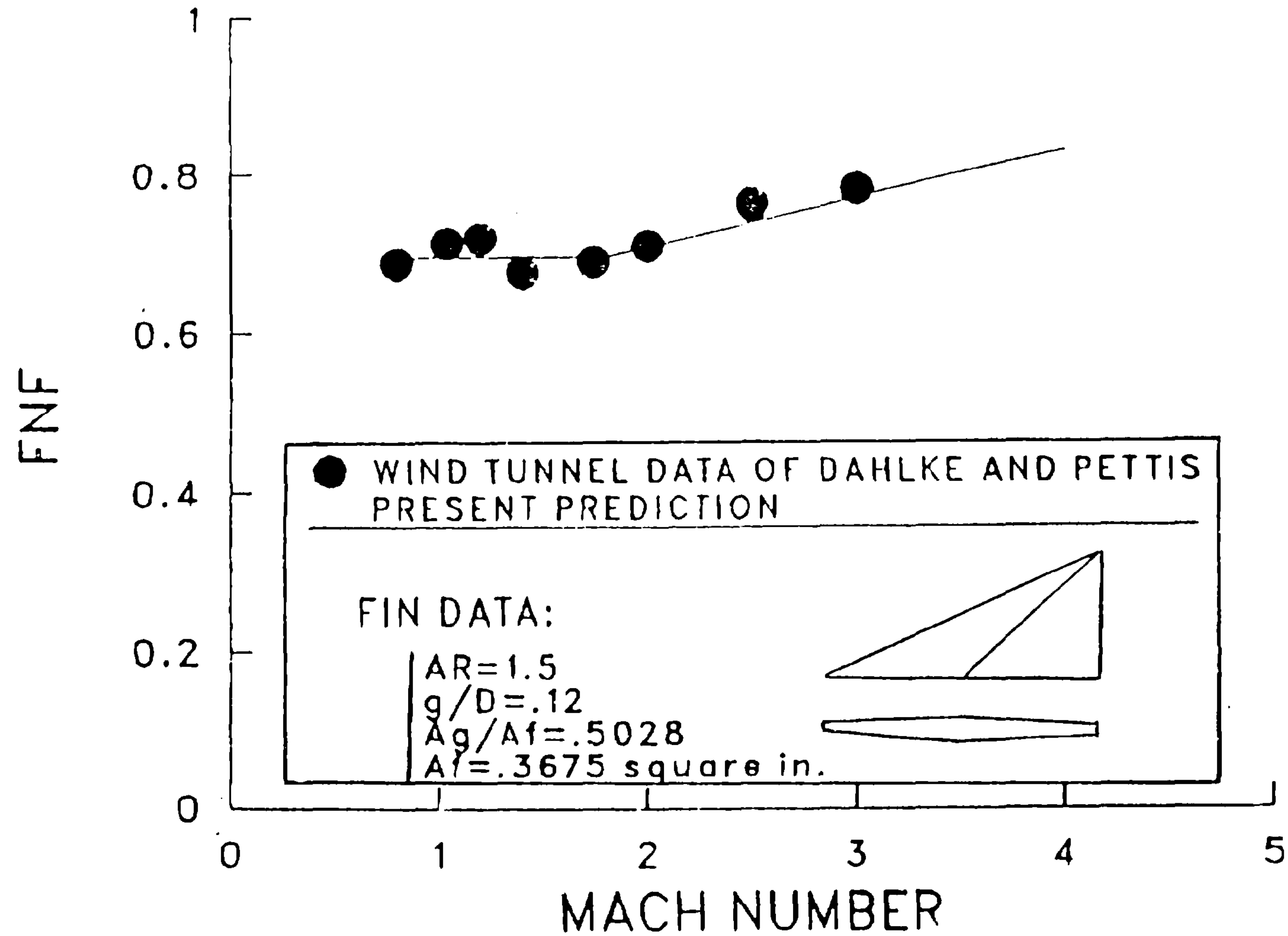

Figure 12. Comparison with data, supersonic speeds (AR = 1.5, g/D = 0.12)

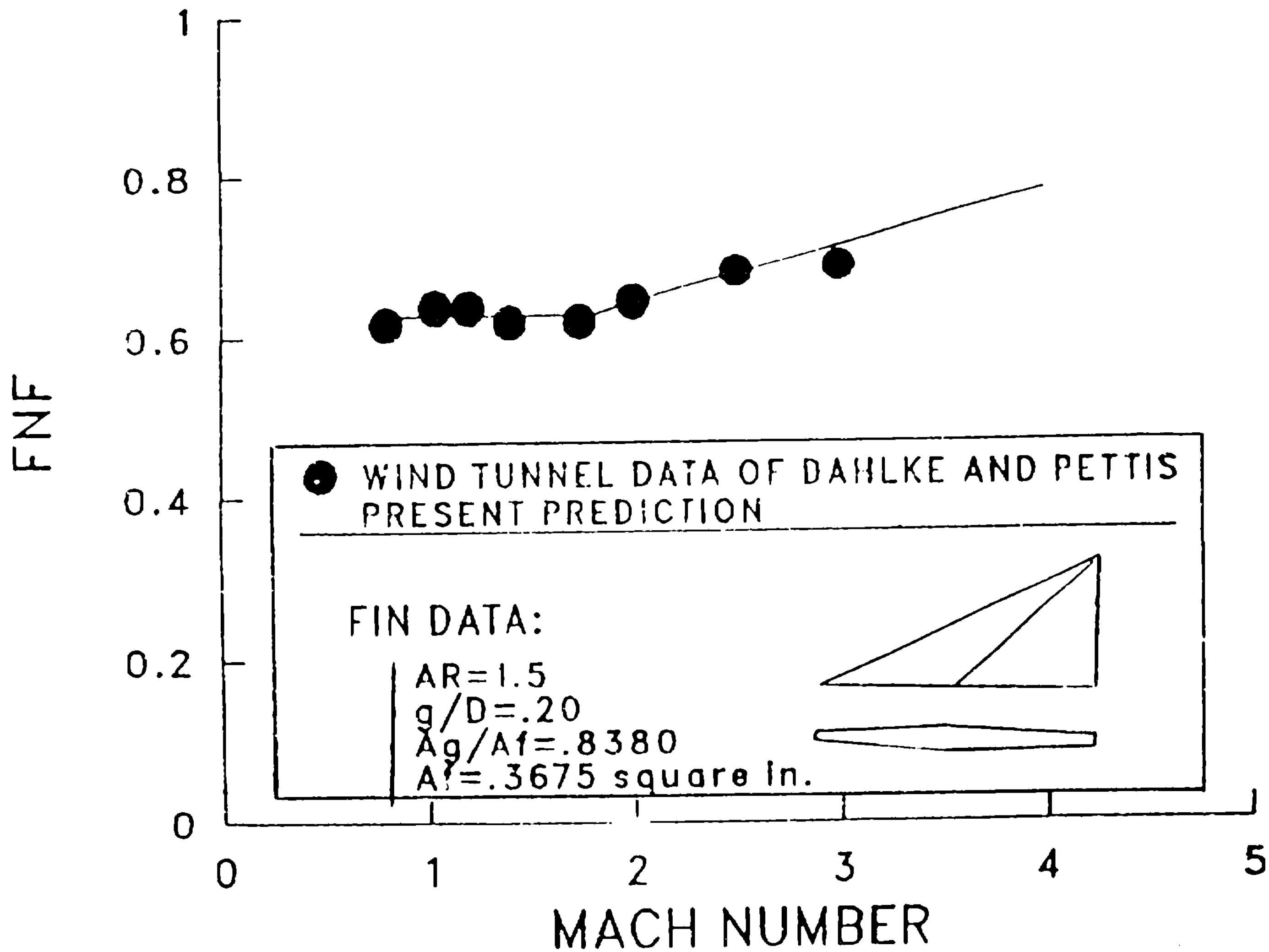

Figure 13. Comparison with data, supersonic speeds (AR = 1.5, g/D = 0.20)

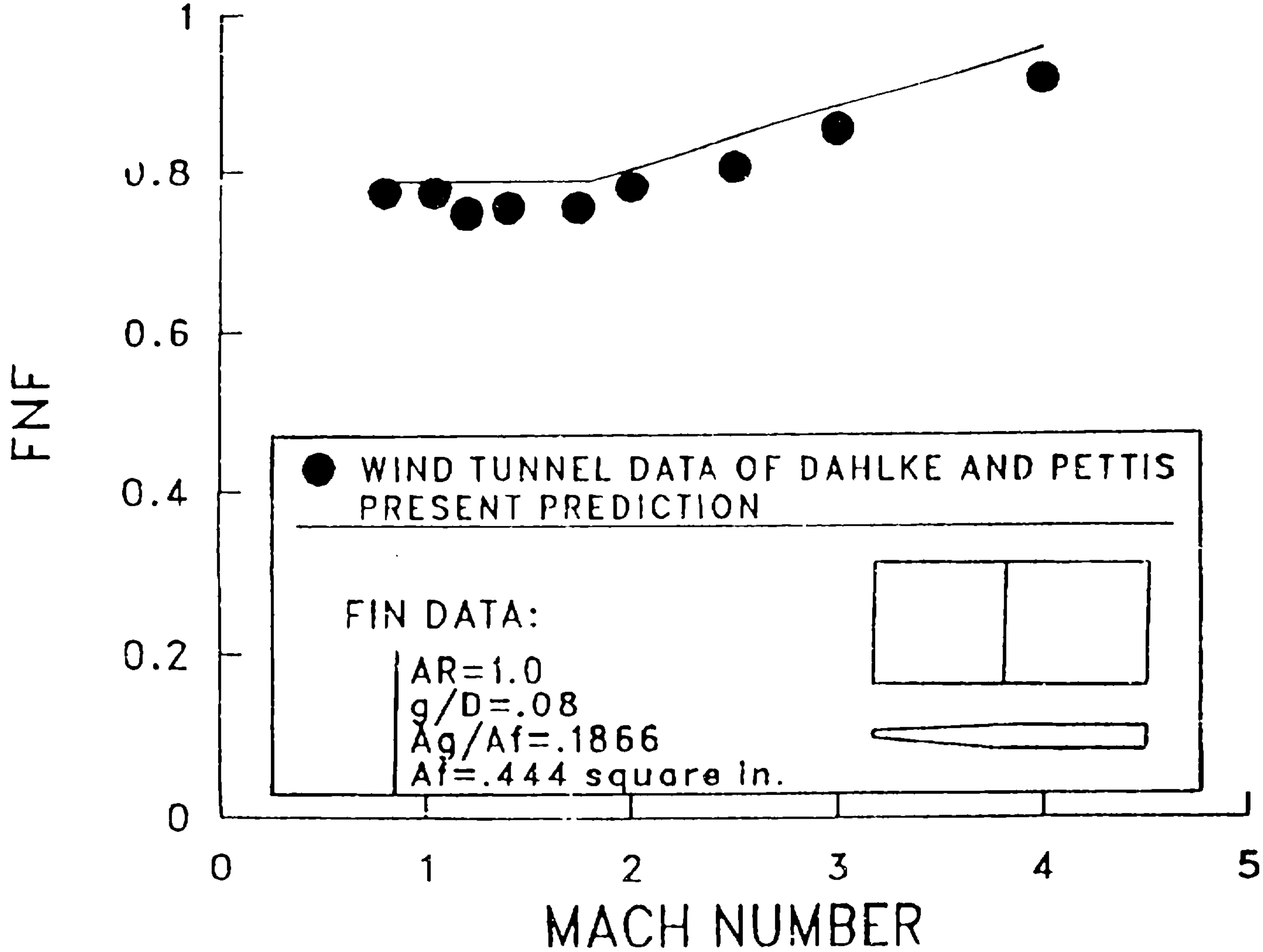

Figure 14. Comparison with data, supersonic speeds (AR = 1.0, g/D = 0.08)

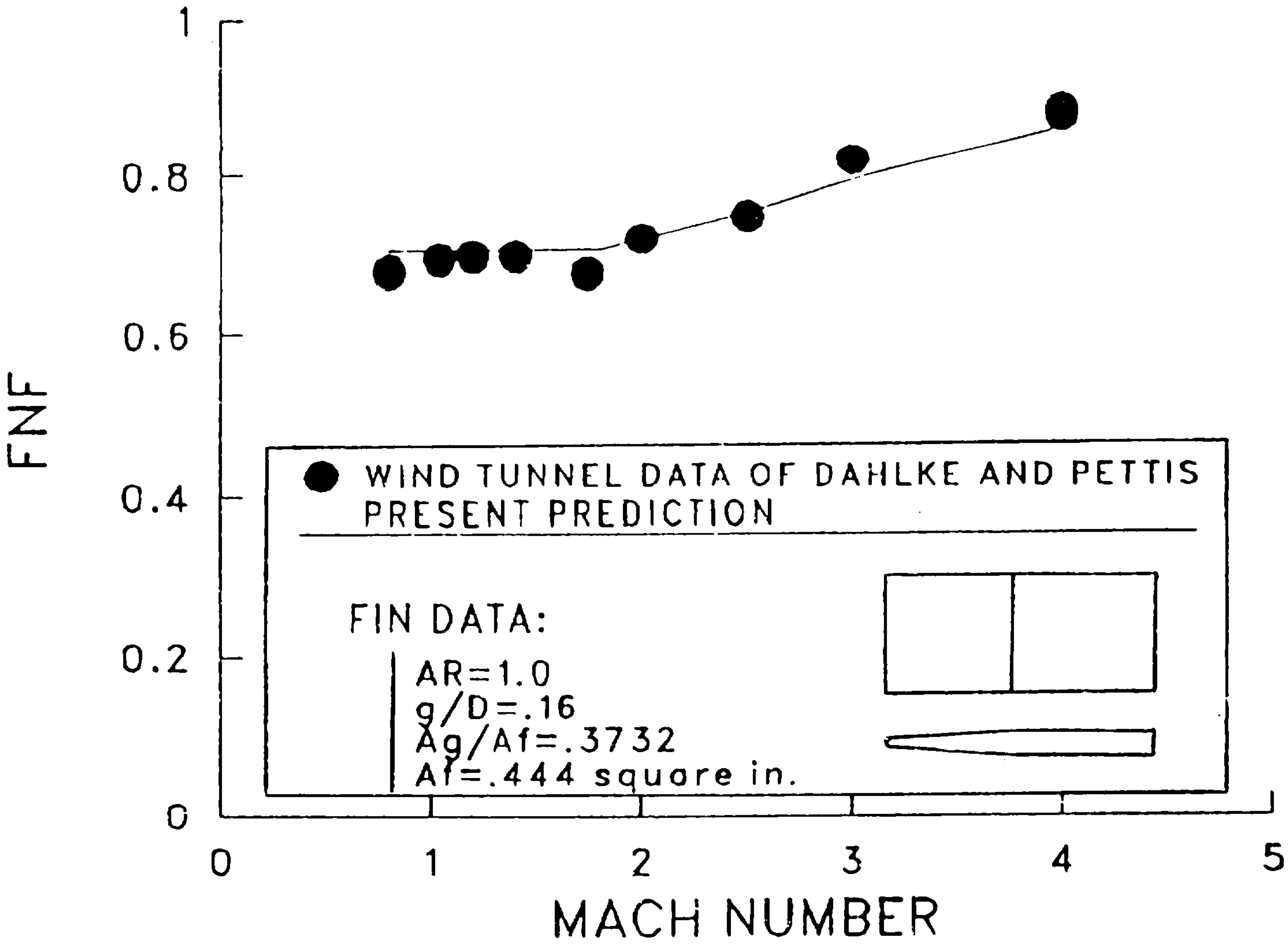

Figure 15. Comparison with data, supersonic speeds (AR = 1.0, g/D = 0.16)

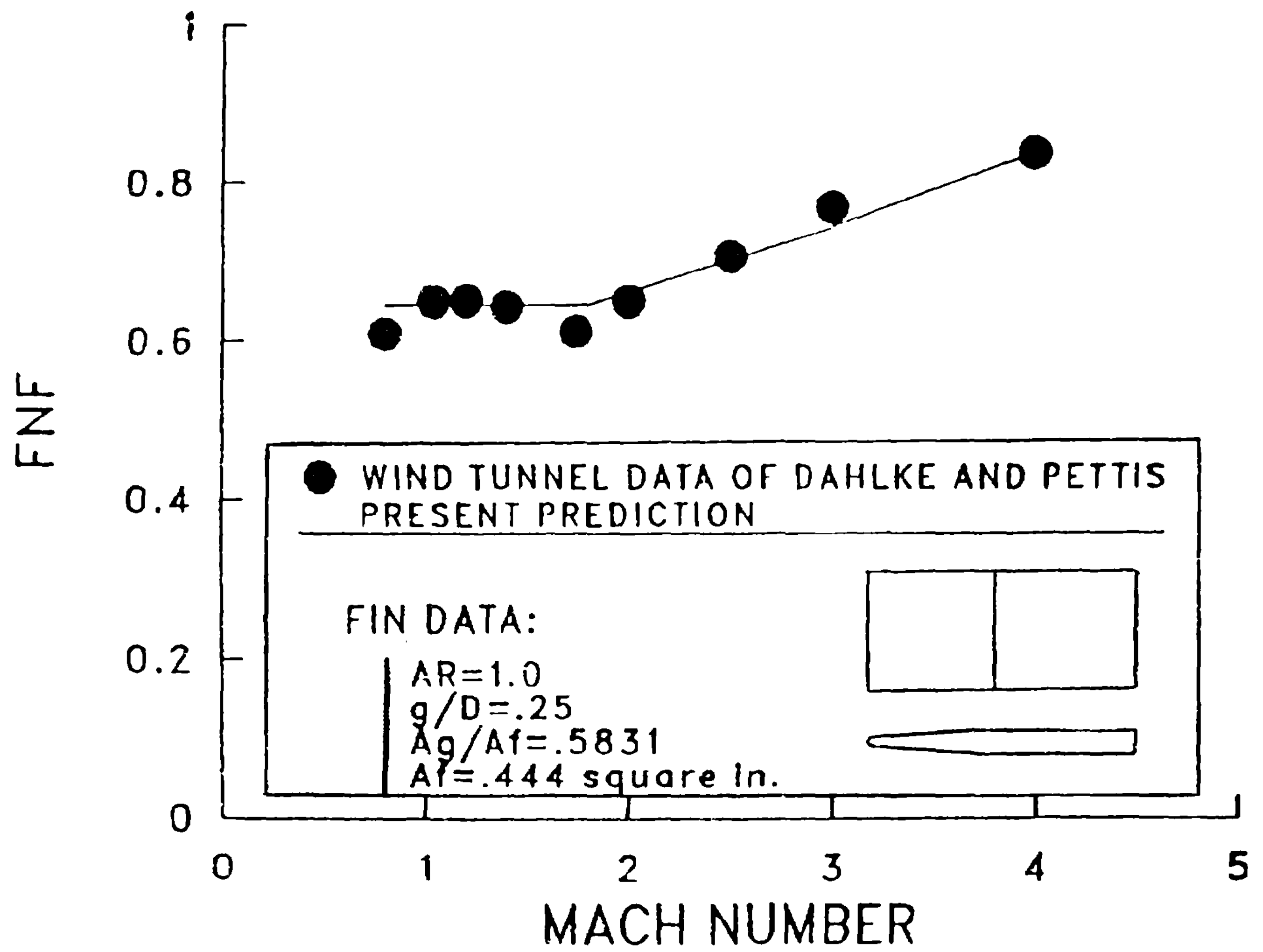

Figure 16. Comparison with data, supersonic speeds (AR = 1.0, g/D = 0.25)

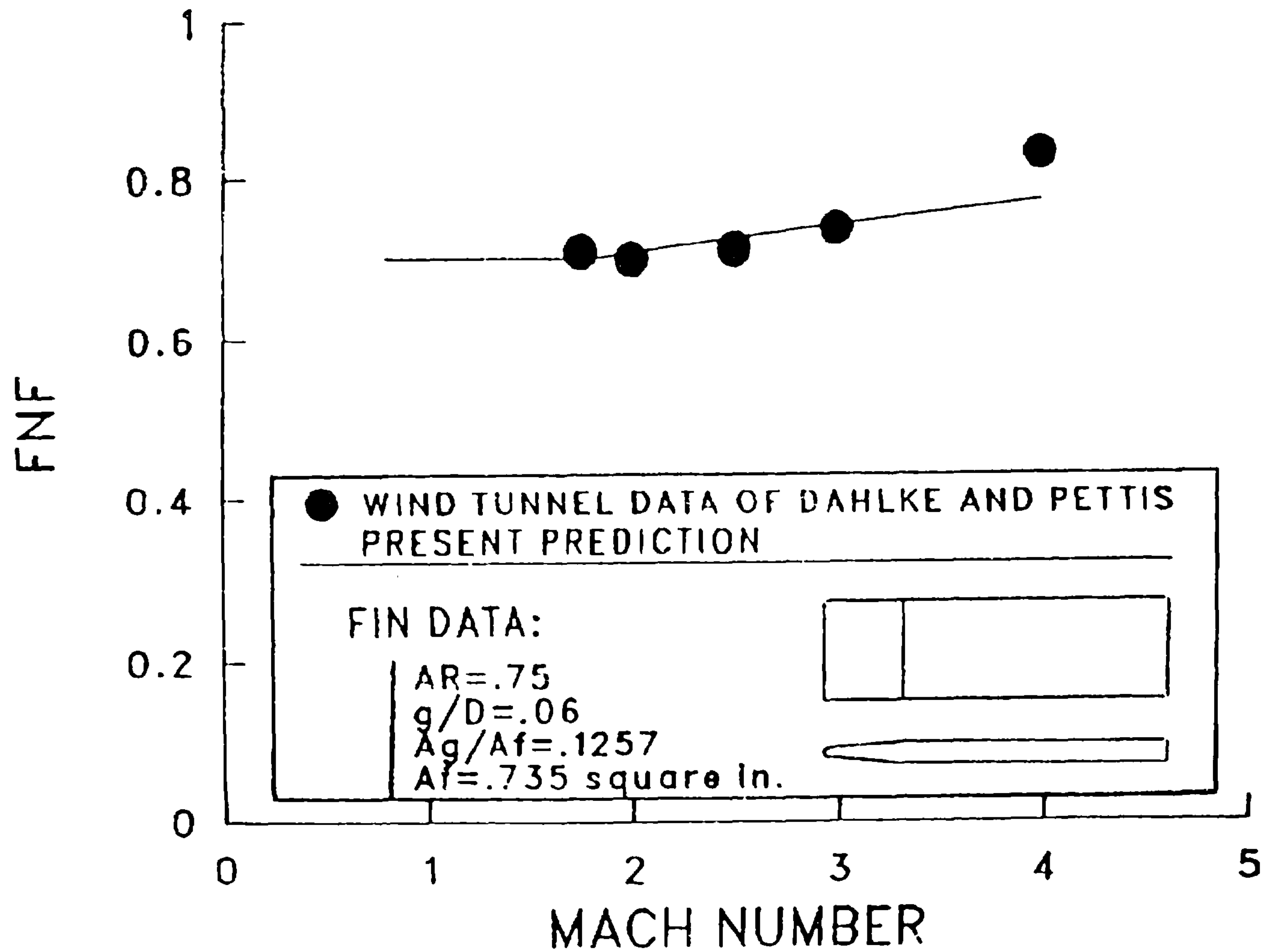

Figure 17. Comparison with data, supersonic speeds (AR = 0.75, g/D = 0.06)

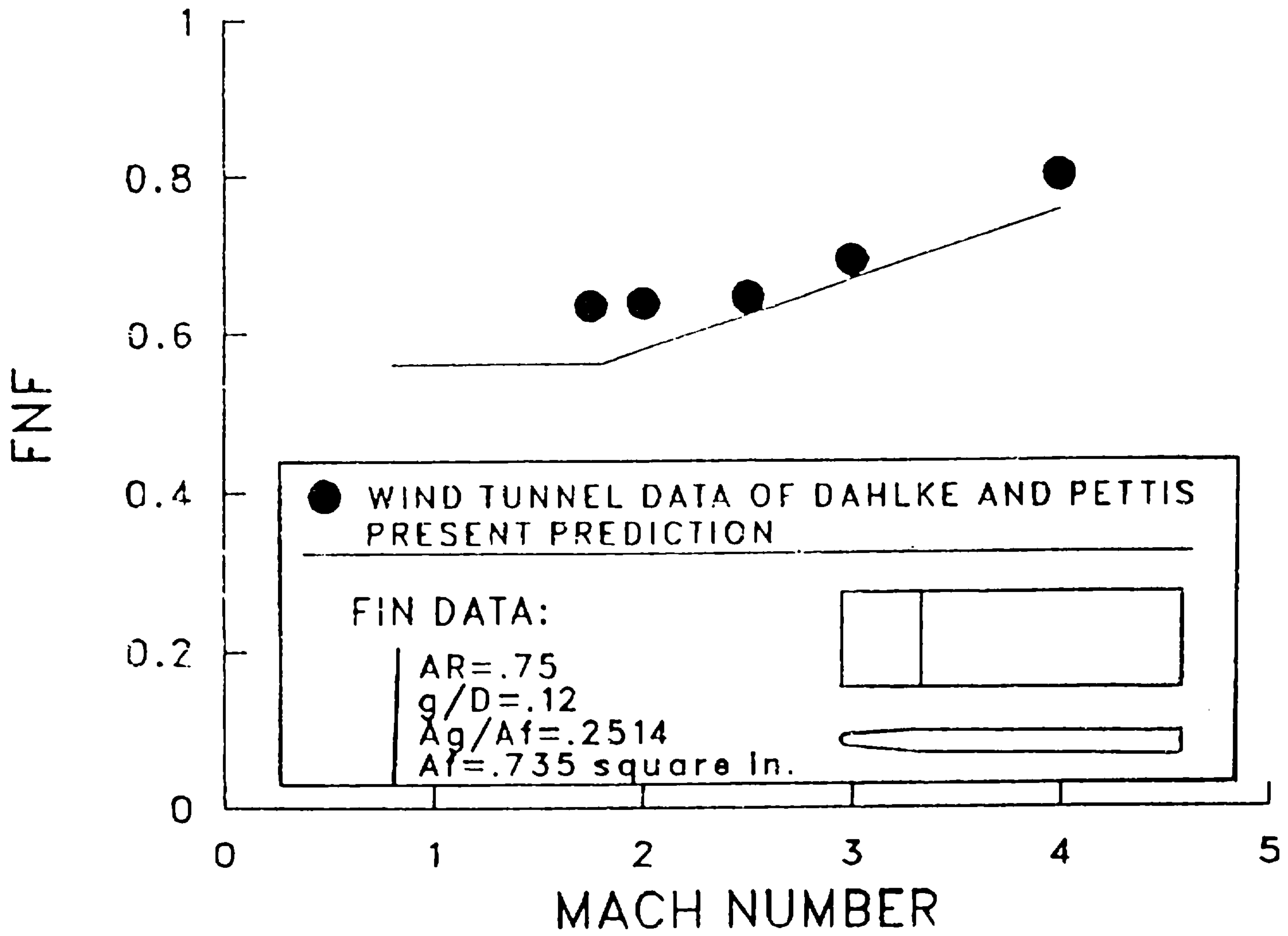

Figure 18. Comparison with data, supersonic speeds (AR = 0.75, g/D = 0.12)

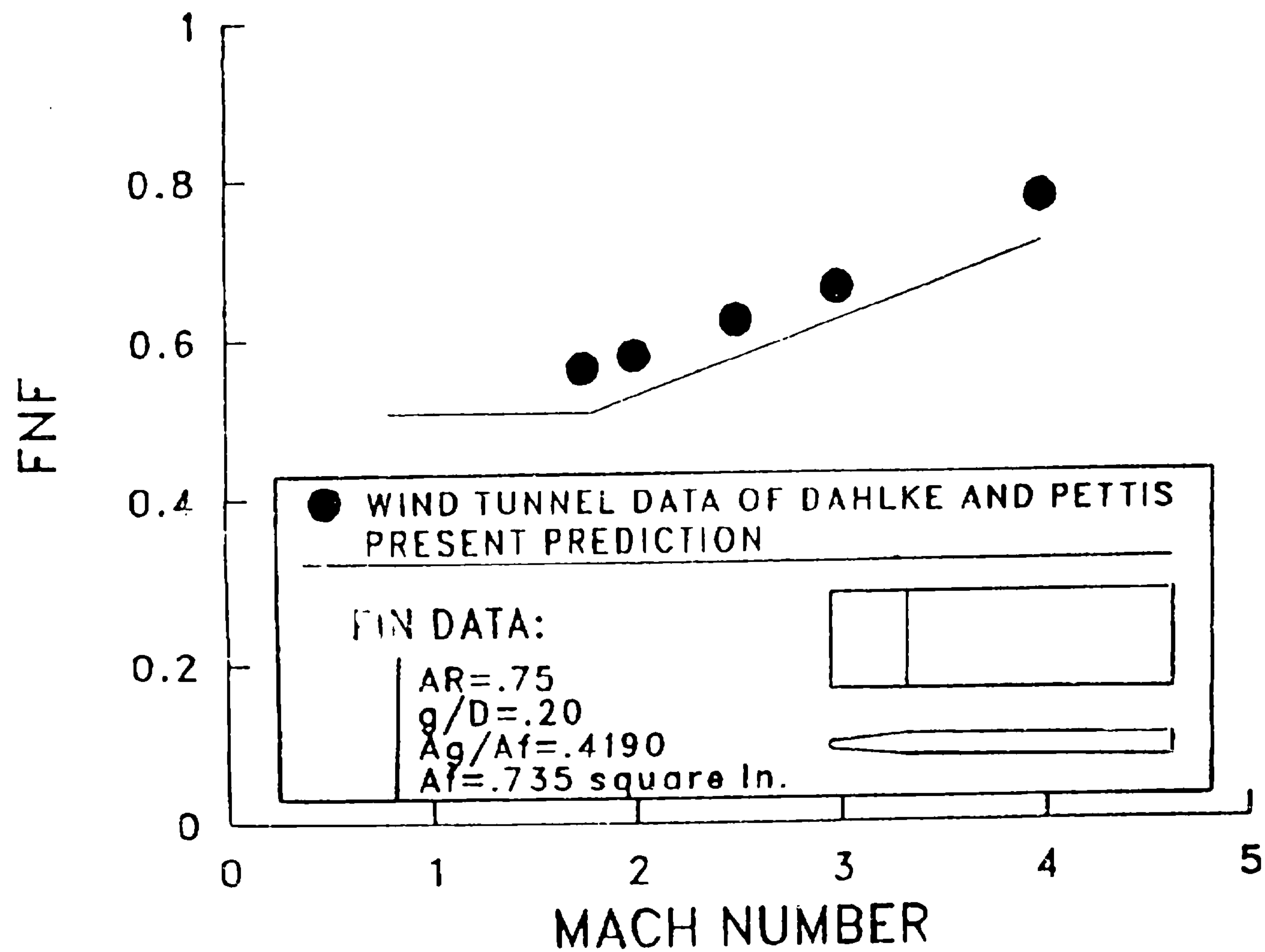

Figure 19. Comparison with data, supersonic speeds (AR = 0.75, g/D = 0.20)

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LIST OF SYMBOLS

A, A_1, A_2	fin total surface area (one side only)
$A_{10}, A_{11}, A_{20}, A_{22}$	fin partial surface area (one side only)
AR	fin aspect ratio, $(2b)^2/S$
A_f	fin surface area (one side only of one fin panel
AF	fin area correlation factor
A_g	streamwise gap area for one fin panel
b	fin semi span (without a gap)
b_1, b_2	a prescribed fin height (without a gap)
BF	boundary layer correlation factor
c, c_1, c_2	fin root chord length
CF	overall fin correlation factor
C_N	normal force coefficient (based on the body reference area) = normal force/qS_{ref}
C_{N_f}	fin (and its interference) normal force coefficient based on the body reference area
$C_{N_{fg}}$	fin (and its interference) normal force coefficient, in presence of a fin gap "g"
C_{N_α}	normal force slope coefficient (per radian), $\partial C_N/\partial\alpha$
$C_{N_{\alpha f}}$	fin (and its interference) normal force slope coefficient (per radian)
$C_{N_{\alpha fg}}$	fin (and the interference) normal forces slope coefficient, in presence of a fin gap "g" (per radian)
CSF	fin chord and span correlation factor
D	body diameter
FNF	fin normal force loss factor, due to presence of a fin gap "g"
g, g_1, g_2	gap height between fin root chord and body surface
GF	fin gap correlation factor
M	Mach number of projectile

q	dynamic pressure of the flow ($0.5\ \rho_\infty U_\infty^2$)
R_e, R_{e1}, R_{e2}	Reynolds number of the projectile per unit length $\rho_\infty U_\infty/\mu_\infty$
R_{e_x}	local Reynolds number of the projectile flow, $\rho_\infty U_\infty x/\mu_\infty$
S	fin surface area (one side) of two fin panels connected without gaps and body diameter
S_{ref}	body reference area, $\pi D^2/4$
SF	fin shape correlation factor
x	distance, along the body axis, from the nose tip
x_{LE}, x_{LE1}, x_{LE2}	distance, along the body axis, from the nose tip to the leading edge of a fin panel, at the fin root section

Greek Symbols

δ	boundary layer thickness
$\delta_{LE}, \delta_{LE1}, \delta_{LE2}$	boundary layer thickness at the leading edge of the fin root section

Subscript

g	indicates the presence of a gap between fin root chord and body surface

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